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3D printing technologies and photopolymer resins used in fixed prosthetic rehabilitation

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Abstract

The utilization of computer-aided design and production has become increasingly prevalent in the dental industry, as in many other fields. Additive manufacturing, a computer-aided production method, has brought about numerous advantages such as fast and precise production, design freedom, and cost and time savings. It is anticipated that 3D printers will become the primary method for digital processing in dentistry in the future. The objective of this article is to offer a comprehensive introduction to the present-day manufacturing methods for fixed prosthetic rehabilitation, focusing on the 3D printing manufacturing and photopolymer resin materials employed in these technologies.

Keywords: Additive manufacturing, 3D printing, Photopolymer resin.

INTRODUCTION

Typically, the phrase ‘‘3D printing’’ is utilized to refer to a method of manufacturing that constructs objects by successfully adding layers, ultimately forming a complete product. This technique is more accurately known as additive manufacturing, and is referred as rapid prototyping as well [1]. 3D printing’s popularity in dentistry has coincided with improvements in computer aided design (CAD) and imaging techniques, such as computer tomography (CT), cone beam computed tomography (CBCT), magnetic resonance imaging (MR), and intraoral or laboratory optical surface scan data. These advancements allow for the planning and printing of dental and maxillofacial prostheses, enabling replacement of lost structure or restorations. The usefulness of 3D printing relies on our ability to generate objects that can be printed [2]. Practising 3D printing in dentistry, complex structures can be created without any wast material, making it more cost effective option than substractive manufacturing techniques in regards to both hardware investment and overall production expenses [3]. Presented evidence indicates that the optimal materials for dental restorations possesses numerous qualities associated with cost effectiveness, durability and exceptional performance. The materials employed for dental 3D printed restorations should possess qualities such as biocompatibility, non toxicity, affordability, and aesthetic appeal, with no change in color or appearance following manufacturing process [4]. Out of the various options available for additive manufacturing, polymer based 3D printing is the most frequently utilized material in dental field. A vast range of polymeric materials, which are used in the production of fixed and provincial dental restorations, dental implants, surgical guide, denture framework, dental splints, and other 3D tissue pattern, can be accommodated by the majority of 3D printers that dentists have access to today [5]. In dentistry a range of 3D printing technologies are in use, however the two most frequently utilized techniques are stereolithography (SLA) and material jetting (MJ) technologies [6]. The objective of this review was to present the utilization of 3D printing techniques and available photopolymer resin materials used in prosthetic dentistry.

CLASSİFİCATİON OF 3D PRİNTİNG TECHNOLOGİES

The International Association for Testing Materials (ASTM) (ISO/ASTM 52900:2021) is responsible for establishing technical standards for various products, materials, systems, and services. Within the ASTM, the additive manufacturing technologies namely 3D printing technologies can be classified into seven categories: Vat Photopolymerization (VPP), Material Jetting (MJ), Material Extrusion (ME), Binder Jetting (BJ), Powder Bed Fusion (PBF), Sheet Lamination (SL), and Direct Energy Deposition (DED) [7].

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Vat Photopolymerization (VPP)

The term vat photopolymerization includes multiple additive manufacturing technologies. Essentially, it refers to the process of using a light source to selectively solidify a liquid polymer resin in layers based on a 3D model. This is done in a step-by-step manner [8]. This approach boast impressive precision in building, with rapid construction speed and exceptional part quality [9]. In a typical vat photopolymerization printer setup, achieving high-quality surface finish and precision of the printed parts largely depends on two key factors: the layer height, which typically ranges from 25 to 100 microns, and the light source resolution, which is determine by the size of the laser spot, varying between 130 and 150 microns. These parameters are crucial in determining the overall quality of the final printed product [10]. However, despite the high resolution, the properties of the resulting 3D printed objects can be influenced by several factors. One of the primary limitations is the amount of time required for printing, while a single layer can be rapidly produced, curing the layer is a time consuming process. Additionally, the need for continuous refilling of the resin tank can led to further delays. Finally, the mechanical characteristics of the printed objects are dependent on the degree of polymerization and the post print curing process [11]. Furthermore, vat photopolymerization processes include: Stereolitography (SLA), Continuous Digital Light Projection (CDLP), Digital Light Processing (DLP), and Two-Photon Polymerization (2PP) [8].

Stereolitography (SLA)

Of all the presently available 3D printing technologies, stereolithography is likely the most popular and also the first commercially accessible rapid prototype technique. This technology employs a photosensitive monomer resin that polymerizes and solidifies under ultraviolet (UV) light exposure. As a result of the beam's absorption and scattering, this reaction only occurs near the surface. A stereolithography machine is comprised of a build platform installed in a vat of resin and a UV helium-cadmium or argon ion laser [12]. Stereolithography technique is preferred in dentistry for digital manufacturing of dental model replicas, surgical guides, provisional dental restorations, and custom trays [13].

Continuous Digital Light Projection (CDLP)

Instead of using a conventional glass window, this method employs digital projection with LEDs and an oxygen-permeable window. By using an oxygen-permeable window, a small "dead zone" is created. The thickness of the "dead zone" created by the oxygen-permeable window is equivalent to the width of a human hair. This enables the liquid resin to flow easily between the printed part and the window interface. This flow of uncured resin significantly enhances the resolution, resulting in a remarkable improvement [14].

Digital Light Processing (DLP)

The realm of digital light processing printers has revolutionized the manufacturing of dental models, and it is a significant application area. Although digital light processing and stereolithography share similarities, they also have several distinctions. For instance, they differ in the type of light source used, as well as the method of controlling the light source for selective resin illumination and curing. In stereolithography, a laser is utilized as the light source, whereas digital light processing employs a projector similar to a movie projection device to illuminate the entire shape of the object being printed on the liquid's surface. Theoretically, digital light processing can produce objects more quickly as each layer does not require a step-by-step laser scan. However, digital light processing printers generally do not provide the high resolution of stereolithography's laser beams. Consequently, digital light processing is better suited for printing larger parts with less intricate details, while stereolithography is more suitable for printing precise parts with complex details [15]. Digital light processing is employed widely in the manufacturing of dental crown restorations, dental bridges, surgical guides, removable dental prosthesis, and dental models as well [13,15].

Two-Photon Polymerization (2PP)

Two-Photon Polymerization is a technique that utilizes a laser beam to produce 3D objects by direct laser writing. The two-photon absorption principle enables achieving resolution below the diffraction limit, which is made possible through polymerization of a photosensitive polymeric material known as a photoresist. This technique is highly preferred in medical applications due to its remarkable ability to create solid polymer objects with resolutions that can be as low as a few nanometers. Unlike conventional 3D printing, the two-photon polymerization technology doesn't involve the layer-by-layer deposition of materials since the solid polymer objects can be directly cured in the resin vat [16].

Material Jetting (MJ)

PolyJet Printing (PP) is another name for material jetting technology, which involves the selective jetting of liquid resin form hundreds of nozzles that is subsequently polymerized. In the polyJet 3D printing process, a liquid photopolymer is jetted into the build tray, and then it is cured instantly using ultraviolet light. This printing method provides a higher degree of printing precision than stereolithography due to its ability to generate a smaller laser spot diameter, typically ranging between 0.06-0.10 mm. This results in the production of smoother and more precise parts. Moreover, polyJet's high-speed raster construction process enables faster printing without the need of post curing process [17,18]. Material jetting printing is commonly used in dentistry to fabricate dental bridges, and surgical guides as well [13,15].

Material Extrusion (ME)

Fused Deposition Modeling (FDM) is a frequently used technology for 3D printing plastic or polymeric materials directly. This is primarily because polymeric materials have a lower softening temperature than metallic or ceramic materials [19]. This technology utilizes hot extrusion process where the material is heated until it reaches a flowable state. As the thermoplastic polymer material heated, it softens and can be squeezed out of a nozzle. With the help of a predetermined nozzle size, the extrusion rate and resolution can be customized for various builds. By applying a layer-by-layer extrusion of material and utilizing successive raster scans for each layer, it becomes feasible to fabricate a 3D object that complies with a CAD design [20]. Compared to alternative manufacturing methods, this specific process exhibits relatively low precision and speed. Additionally, the quality of the final product is limited by the thickness of the material nozzle. When using this process to produce components that require high precision, it is essential to consider the effect of gravity and surface tension. The typical layer thickness for this process can range from 0.178mm to 0.356mm [6].

Binder Jetting (BJ)

In the process of binder jetting, a similar approach to material jetting is followed, but instead of using a a material jet to create the 3D object, a binder is dispensed onto a bed of powder material. The binder causes the powder particles to adhere to each other, resulting in the formation of the desired object [21]. This process selectively bonds powder materials using binder droplets. This process involves several steps, including infiltration or sintering to archive mechanical strength. Although this process has some restrictions, such as challenges with fatigue strength, surface finish, and thermal distortion, binder jetting has the potential to excel in ceramic dental prosthesis applications. This is because it is compatible with various ceramic materials and shares similarities with traditional manufacturing routes. However, attaining strength and precision in the parts printed with binder jetting is contingent on several factors, such as nominal dimensions, powder materials employed, parts orientations, geometric features, and the parts location in the print bed [22].

Powder Bed Fusion (PBF)

The powder bed fusion printing process is similar to binder jetting in terms of procedural steps, except that instead of using binder droplets, thermal energy is employed to bind the powder. The energy source fuses the powder once each layer is added, resulting in a layer-by-layer construction of the 3D object. However, there are significant distinctions during the printing process, including the requirement for preheating and an oxygen-free environment to avoid feedstock powder oxidation. Commonly utilized protective gases include vacuum for electron beam source, argon for reactive powder, and nitrogen for non-reactive powder. Depending on the thermal energy source utilized, PBF is categorized into laser and electron beam-based processes [23]. Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Laser Melting (SLM), and Multi Jet Fusion (MJF) technologies utilize this method. Selective laser sintering involves creating a solid plastic objects by sintering layers of powdered material [24]. PBF is a printing process commonly used for manufacturing dental implants, dental bridges among other medical applications [15].

Sheet Lamination (SL)

Sheet lamination is a process where thin sheets are fused together using either an adhesive or a heat source to create a 3D object. This process involves layering sheets on top of each other and bonding them for the final object [19]. SL doesn't require support during the printing process. However, to prevent any harm or damage to the final product, it is important to handel the waste material with caution during processing. Cleaning up the parts can be a laborious process, and it is important to have clear understanding of the final part's appearance to avoid damage during waste removal. Paper- based systems may require additional sealants and coating to prevent handling issues, while polymer SL is generally less sensitive to damage. In metal SL, sheets are typically cut first and then stacked to form the 3D object, eliminating the need for support removal [25].

Direct Energy Deposition (DED)

Direct energy deposition is a process used to create objects by melting materials such as aluminium, titanium, copper, or stainless steel in powder or wire form using a focused energy source [26]. A nozzle dispenses material onto a surface while moving around a stationary object, facilitating accurate material placement in predetermined locations. Though this technique can be utilized to fabricate entire parts, it is mainly employed for repairing or supplementing existing objects. When combined with Computer Numerical Control (CNC) machining, DED can achieve precise finishes on manufactured parts. However, direct deposition has some limitations, such as the necessity for a significant quantity of inert gas in fully inert chambers, the need for post-processing to obtain the desired finish, and inefficiency due to leftover material that the nozzle does not melt [24]. The most widely employed direct energy deposition techniques are laser direct deposition (LDD) methods, which comprise laser cladding, laser melting injection, and laser engineered net shaping. Another method is electron beam direct manufacturing (EBDM). These procedures can be categorized as either surface modification or 3D part manufacturing techniques, depending on the desired outcome [27].

Photopolymer resins used in fixed prosthetic dentistry

For printing three dimensional parts using multifunctional composites, photopolymer resins have been utilized. Dental resins, including methacrylate-based ones (such as polymethyl methacrylate or PMMA), epoxy-based ones, and cationic-based ones, can be combined with different fillers, such as glass, carbon, or ceramic fibers and particles [24]. Photopolymer resins are a preferred materials for 3D printing in dentistry due to their flexibility in design, ease of use, and cost effectiveness. The mechanical, chemical and physical properties of photopolymers are influenced by their chemical composition, degree of curing, and mostly polymer structure. When designing and synthesizing materials for 3D printing, we can manipulate the material properties at the molecular level, and process them into suitable size, shape, and rheology for the printing process. The manufacturing process of 3D printing involves various parameters, including temperature and heating/cooling rate, that can significantly influence the microstructures of the material. These microstructures, such as the size of crystallinity, play a crucial role in determining the mechanical and other properties of the printed objects. Therefore, it is crucial to comprehend the relationship between structure, process, and properties in 3D printing [28].

Photopolymer resins chemical composition

Photopolymer resins typically consists blend of different components such as monomer, oligomer, photoinitiators, and various additives. In the context of 3D printing, photopolymer resins are used and these resins comprise of oligomers and monomers that undergo polymerization under a light source [8]. Ultraviolet light with a wavelength ranging from 355 to 405 nm is typically used for polymerizetion. Oligomers are important parts in forming the backbone of the polymer chain which ultimately determines the physical properties of the printed objects, including its hardness, strength, adhesion, and surface finish. Methacrylate monomers are frequently used in resin based composites obtained via photopolymerization. These monomers form an organic matrix that has a high reactivity and degree of crosslinking. The two most commonly used monomers in dental composites are BisGMA and TEGDMA. UDMA is another acrylate monomer that is frequently utilized alongside other common monomers like BisGMA, TEGDMA, and ethoxylated BisGMA (BisEMA) which also undergo polymerization [29,30]. Chemical compounds known as photoinitiators play a crucial role in the polymerization process. These compounds break down into reactive molecules when exposed to light, which triggers the polymerization of the resin. Essentially, the photoinitiator converts the energy from the light into chemical energy, which leads to the polymerization process. Choosing the appropriate photoinitiating system is crucial for dental composites, as it impacts the efficiency of the photopolymerization reaction and the compatibility of the composite with different light sources [23]. Light-cured composites usually employ a photoinitiating system based on camphorquinone (CQ) for the polymerization process. In this system, a tertiary amine acts as the primary co-initiator, absorbing radiation within the range of 200 to 300 nm, making it a commonly used component. In order to overcome the limitations of the CQ-based photoinitiating system, 3D printing resin systems primarily utilize phosphine oxide systems [31,32]. Unlike CQ, these systems do not require a co-initiator and offer several benefits, such as a high degree of conversion, a rapid rate of polymerization, and color stability. Most frequently used is phenylbis phosphine oxide (BAPO) due to its high light absorptivity and its high reactivity. In dental applications, mono-acylphosphine (MAPO) is another photoinitiator that is frequently used, often in combination with phenylbis phosphine oxide. One of the earliest mono-acylphosphine initiators to be commercially available is diphenyl phosphine oxide, commonly known as TPO. A new photoinitiator, ethyl phenylphosphinate (TPO-L), has been proposed for use as novel photoinitiator in 3D printing applications. The ideal photopolymer resin should meet two main requirements: it should have a low viscosity and provide high performance [33-35].

CONCLUSION

In the present day, the most significant obstacle for a dentist is adapting to a digital workflow and integrating new technologies and equipment into their regular practice. Therefore, 3D printing is an important technique that offers high printing speed and precision without relying on any specific models. The swift growth and expansion of additive manufacturing technologies are expected to persist as the selection of printable dental materials expands. The development of biocompatible, high-performance, and novel materials will broaden the application of 3D printing, making it a promising technology. Nevertheless, the adoption of new technology entails a fresh set of responsibilities. Gaining knowledge about how these materials compare with conventional materials will empower dental professionals to create more comprehensive treatment plans, resulting in a higher quality of care for patients as well.

Conflict of Interest

None declared.

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